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A BIM-ENABLED FRAMEWORK FOR RISK ASSESSMENT OF REINFORCED CONCRETE, STRUCTURAL STEEL AND COMPOSITE SYSTEMS DURING CONSTRUCTION

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SUMMARY: *Construction-phase risk in building structures changes continuously as elements are installed, temporary supports are placed and removed, and trades and equipment overlap in time and space. Conventional risk registers record hazards but rarely preserve the structural object, temporary state, schedule window and exposed group to which each hazard applies, which limits their usefulness when the construction sequence changes. This paper proposes a Building Information Modelling (BIM)-enabled framework for identifying, assessing and communicating construction-phase risks across three structural system families: cast-in-place reinforced concrete (RC), structural steel and steel–concrete composite construction. The framework comprises a risk information model linking model objects, temporary works, schedule activities, work zones, exposed groups, equipment, hazard scenarios, controls and evidence; a common likelihood–consequence–exposure screening index with an escalation rule for high-consequence hazards; and an eight-step workflow supporting 4D visualisation and reassessment. Structural system is treated as a classification dimension that preserves system-specific hazard mechanisms, not as a proxy for risk level. An analysis of the screening index shows that its 125 rating combinations collapse to 30 distinct scores and that a one-step change in a single rating alters the decision band in 27% of cases, which motivates explicit provenance, confidence and escalation fields. The paper does not report an implemented prototype, project data or expert ratings; it is a conceptual and design contribution. A three-phase validation protocol covering expert review, technical evaluation and comparative case studies is specified, with measurable hypotheses, so that traceability, reliability and practical value can be tested empirically in later work. The framework is intended to support, not replace, engineering judgement, temporary-works design and statutory safety duties.*

KEYWORDS: *building information modelling; construction risk; structural systems; 4D BIM; temporary works; safety risk assessment; information model*

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1. INTRODUCTION

Construction-phase risk is not constant over the life of a project. It changes as structural elements are installed, temporary support conditions evolve, workspaces become congested, and different trades and equipment operate concurrently. The risk profile of a building therefore depends not only on its final structural form but also on the sequence through which that form is achieved. A completed reinforced concrete (RC) frame does not reveal the temporary instability and access hazards associated with formwork, reinforcement fixing, concrete placement and reshoring. A completed steel frame does not represent the erection-stage risks associated with lifting, temporary bracing, incomplete connections and work at height. Failures of temporary works illustrate the point: falsework collapses have repeatedly been triggered by concreting operations but enabled by deficiencies in bracing, connections, foundations and design review (Hadipriono & Wang, 1986), and construction accidents more generally arise from the interaction of worksite, equipment, worker and upstream management and design factors (Haslam et al., 2005).

Building Information Modelling (BIM) connects geometric, semantic and schedule information that is otherwise distributed across drawings, method statements, risk registers and construction programmes. Research has demonstrated the use of BIM and 4D models for construction safety planning, hazard visualisation and the analysis of spatial–temporal exposure (Zhang & Hu, 2011; Jin et al., 2019; Tran et al., 2021), and recent work has combined BIM with rule-based assessment, simulation and probabilistic modelling (Sorbi et al., 2024; Kim et al., 2024; Khodabakhshian et al., 2025).

1.1 Research gap

Despite this progress, two limitations are evident in the literature reviewed in section 2. First, much BIM-based safety research is organised around generic hazard classes, such as falls from height or struck-by events, or around the regulatory content of safety rules, rather than around the construction logic of a particular structural system. A generic hazard register cannot show that falsework instability during concrete placement and frame instability before permanent bracing is complete are different mechanisms, with different temporal windows, information needs and controls. Second, risk-scoring schemes are commonly adopted without examining the properties of the scale itself. Ordinal likelihood–consequence matrices are known to have limited resolution and can misrepresent relative risk (Cox, 2008; Duijm, 2015), yet BIM-based tools often present such scores as colour-coded outputs whose provenance and sensitivity are not visible to the user.

A framework is therefore needed that (i) preserves system-specific hazard mechanisms and temporary structural states in the information model, (ii) uses a common assessment logic so that scenarios can be compared without being collapsed into a single undifferentiated score, and (iii) makes the limitations of that logic explicit through provenance, confidence and escalation rules.

1.2 Aim and research questions

The aim is to develop a traceable, schedule-aware information framework for identifying and assessing construction-phase risks associated with different structural systems. The following questions guide the work:

- RQ1. Which construction-stage hazards and risk-generating conditions are distinctive to RC, structural steel and composite structural systems?
- RQ2. How can structural objects, temporary works, construction activities, spatial exposure and control measures be linked in a BIM-enabled risk information model?
- RQ3. How can a common risk-assessment logic support comparison across structural systems while retaining system-specific hazard mechanisms, and what are the limits of that logic?

- RQ4. What validation strategy is required to establish the reliability, usability and practical value of the framework?

1.3 Scope and contribution

The scope is limited to building superstructure construction and associated temporary states. Occupational safety and temporary structural stability are the primary risk domains; quality, schedule and logistics consequences are secondary. The paper does not undertake structural design verification, certify temporary works, or estimate accident probabilities from an empirical dataset. Its contributions are: (1) a structural-system-oriented risk information model with explicit representation of temporary works and intermediate states; (2) a common screening index with an escalation rule, together with an analytical examination of the index that identifies its resolution and sensitivity limits; (3) a traceable eight-step workflow for assessment, 4D visualisation and reassessment; and (4) a three-phase validation protocol with defined hypotheses and measures. The contribution is conceptual and methodological. No claim is made that the framework improves safety outcomes; that claim requires the empirical testing specified in section 7.

1.4 Structure of the paper

Section 2 reviews related work and identifies the research gap. Section 3 describes the research design and design principles. Section 4 presents the framework, including the information model, the representation of temporary states, the risk estimation model and the assessment workflow. Section 5 applies the framework to illustrative scenarios for the three structural system families. Section 6 discusses the findings, critically appraises the scoring model and states limitations. Section 7 specifies the validation protocol, and section 8 concludes.

2. LITERATURE REVIEW

The review is organised around four themes that bear directly on the framework: BIM and 4D BIM for safety planning, digital representation of hazard knowledge, risk quantification under uncertainty, and the construction-stage behaviour of temporary works. It is a focused, purposive review rather than a systematic one; its function is to establish the technological and methodological basis of the framework and to locate the gap that the framework addresses.

2.1 BIM and 4D BIM for construction safety planning

Systematic reviews indicate that BIM is increasingly used in safety management and that its adoption at the design stage may help reduce accidents, with the identification of tasks, working areas and associated hazards identified as a particular strength (Martínez-Aires et al., 2018). Early demonstrations of the approach used 4D models to analyse conflicts and structural safety problems during construction (Zhang & Hu, 2011), and BIM-based fall-hazard identification and prevention showed that rule-based checking of model geometry against safety requirements can be automated (Zhang et al., 2015b). Jin et al. (2019) used 4D BIM to assess construction risks at activity and daily planning levels during the design phase, supporting prevention through design, while Lu et al. (2021) proposed a BIM-integrated assessment using likelihood, consequence and exposure and applied it to the comparison of design alternatives.

The role of time and changing site conditions is reinforced by Tran et al. (2021), who linked 4D BIM with accident-case analysis to identify spatial–temporal exposure, and by Kim et al. (2024), who developed a 4D BIM-based framework integrating safety regulations and rule modelling. Together these studies indicate that model geometry alone is insufficient: schedule, resources, workspaces and changing site configurations are also required. They also indicate a methodological pattern relevant here, namely that the most developed BIM safety methods concentrate on geometry-driven hazards such as edges, openings and workspaces, where the model supplies the evidence needed to apply a rule.

2.2 Hazard knowledge, ontologies and rule-based checking

A BIM-based risk process depends on structured hazard knowledge. Zhang et al. (2015a) proposed an ontology-based semantic model of construction safety knowledge to support automated job hazard analysis. Collinge et al. (2022) presented a BIM-based safety risk library to organise and communicate safety knowledge, and Johansen et al. (2023) developed a hazard ontology and 4D benchmark model for automated safety requirement analysis, with attention to falls from height and struck-by hazards. Sorbi et al. (2024) integrated 4D BIM with agent-based simulation to represent interactions between site entities and to visualise exposure. These contributions provide useful foundations for associating hazards with model objects, work activities and spatial conditions. Their emphasis, however, is on reusable hazard knowledge and rule execution; the structural behaviour of temporary configurations, which depends on construction sequence and on engineering design rather than on geometric rules alone, is not their primary focus.

2.3 Risk quantification, uncertainty and the limits of ordinal scoring

Quantifying construction risk is complicated by data scarcity and uncertainty. Khodabakhshian et al. (2025) used expert elicitation and Bayesian networks to address limited and unstructured project data, and Hallowell and Gambatese (2009) illustrated how structured expert judgement can be used to evaluate the effectiveness of construction risk-mitigation measures. These approaches are relevant to structural-system comparison because project records are rarely consistent enough to support simple frequency-based estimates. A framework should therefore distinguish measured incident frequencies from expert-judgement ratings and record the source and confidence of each assessment.

At the same time, the ordinal likelihood–consequence matrices that underlie many practical schemes, and the multiplicative indices derived from them, have well-documented weaknesses. Cox (2008) showed that risk matrices can assign higher qualitative ratings to quantitatively smaller risks and can compress ranges so that very different risks receive the same rating, and Duijm (2015) set out design recommendations intended to limit such inconsistencies. ISO 31000 frames risk assessment as a process of identification, analysis and evaluation within a defined context and requires that its basis and uncertainty be communicated (International Organization for Standardization, 2018). The implication for a BIM-based tool is that an ordinal score is a prioritisation aid whose use must be bounded by explicit rules, and that its properties should be examined rather than assumed.

2.4 Temporary works and structural-system-specific hazards

Temporary works are central to construction-stage structural risk. A study of falsework failures in concrete structures identified triggering, enabling and procedural causes, with impact forces from concreting frequently acting as the trigger and with deficiencies in bracing, components, connections, foundations and design review acting as enabling or procedural causes (Hadipriono & Wang, 1986). This causal structure, in which an initiating event is converted into a failure by latent conditions, is directly relevant to information modelling because the latent conditions are properties of objects and processes that can, in principle, be recorded and checked. Kim et al. (2018) developed a BIM-driven automated decision-support system for the safety planning of temporary structures, demonstrating the feasibility of linking temporary-structure information to safety decisions.

Structural steel and composite construction raise analogous issues with different mechanisms: stability of the partially erected frame before permanent bracing and connections are effective, the sequencing of lifting and release, and the transition from steel-only to composite behaviour as decking, connectors, reinforcement and concrete are added. These mechanisms are described in engineering guidance and incident investigation, but, as far as the reviewed BIM safety literature indicates, they are not systematically represented as comparable, schedule-linked scenario families in a common information model.

2.5 Synthesis and research gap

Table 1 summarises the principal studies and the residual gap relative to the present aim. The gap statements reflect the author's reading of the published abstracts and the descriptions in the cited sources; they identify emphasis, not deficiency, and should not be read as a criticism of the cited work, which pursued different objectives.

Table 1: Synthesis of selected BIM-based safety and risk studies and the residual gap addressed in this paper. † Gap statements indicate emphasis based on the reported abstracts, not shortcomings of the cited studies.

Study	Main contribution (as reported)	Residual gap relative to this study†
Zhang & Hu (2011)	BIM- and 4D-based analysis of conflicts and structural safety problems during construction	Early method; no common cross-system risk index or explicit provenance of ratings
Zhang et al. (2015a, 2015b)	Ontology for automated job hazard analysis; BIM-based fall-hazard identification and prevention	Geometry- and rule-driven hazards; temporary structural stability not the focus
Martínez-Aires et al. (2018)	Systematic review of BIM and safety management	Review level; does not propose a structural-system-specific information structure
Kim et al. (2018)	BIM-driven decision support for safety planning of temporary structures	Focus on temporary structures; no comparison across structural-system families
Jin et al. (2019)	4D BIM risk assessment at activity and daily levels in design phase	Design-phase prevention; temporary states of specific systems not modelled in detail
Lu et al. (2021)	BIM-integrated L, C, E assessment for comparing design alternatives	Scoring properties and sensitivity not examined; provenance not a core element
Tran et al. (2021)	4D BIM with accident-case analysis for spatial–temporal exposure	Exposure-centred; structural-system mechanisms not differentiated
Collinge et al. (2022)	BIM-based construction safety risk library	Knowledge organisation; scenario linkage to temporary structural states not the focus
Johansen et al. (2023)	Hazard ontology and 4D benchmark model for automated requirement analysis	Falls and struck-by emphasis; instability scenarios outside the stated focus
Kim et al. (2024)	4D BIM rule-based framework integrating safety regulations	Regulation-driven; engineering-judgement scenarios for temporary works not central
Sorbi et al. (2024)	4D BIM with agent-based simulation for site risk estimation	Simulates site-entity interaction; structural-system classification not central
Khodabakhshian et al. (2025)	Elicitation-based Bayesian network for risk identification and assessment	Generic project risks; not linked to BIM objects and schedule windows

The synthesis supports three conclusions that shape the framework. First, linking hazards to objects, activities and time is well established, so the framework adopts rather than re-invents that principle. Second, the representation of temporary structural states and construction-sequence dependencies across structural systems is comparatively underdeveloped. Third, the properties of ordinal scoring are rarely examined within BIM-based tools. The framework in section 4 addresses these points directly.

3. RESEARCH DESIGN AND METHOD

3.1 Design-science orientation

The study adopts a framework-development approach informed by design-science research, in which an artefact is designed to address an identified problem, grounded in existing knowledge, and then evaluated (Hevner et al., 2004; Peffers et al., 2007). The artefact here is an information model and assessment workflow. Within the design-science cycle, this paper covers problem identification, definition of objectives, and artefact design; demonstration through illustrative scenarios is limited to analytical application, and formal evaluation is specified as a protocol in section 7 rather than reported. This scoping is deliberate: presenting a design with a stated evaluation plan is more transparent than presenting unvalidated results as findings.

3.2 Evidence base and literature selection

The literature cited in section 2 was selected purposively to cover BIM and 4D safety planning, hazard knowledge representation, risk quantification under uncertainty and temporary-works failure. Sources were peer-reviewed journal articles, an ITcon article relevant to the target journal, and international standards. The review is not represented as exhaustive or systematic, and the conclusions drawn from it are limited accordingly. The hazard scenarios in section 5 were derived analytically from the construction sequences of the three system families and from the failure mechanisms described in the cited literature; they are not observations from a specific project.

3.3 Framework design principles

Six principles guided the design:

- **Traceability:** each risk record is linked to one or more structural objects, construction activities, locations and responsible parties.
- **Temporal sensitivity:** risk is evaluated for a defined construction activity and time window, not solely for the completed building.
- **System specificity:** hazard scenarios reflect the construction sequence and temporary state of each structural system.
- **Comparability with differentiation:** common definitions of likelihood, consequence and exposure are used across systems, while hazard descriptions and controls remain context-specific.
- **Information provenance:** each rating records whether it is based on incident data, project documentation, expert judgement or an assumed planning value, together with a confidence level.
- **Actionability:** each high-priority risk is connected to preventive or mitigative controls, an owner, a due date and a verification status.

3.4 Structural-system and activity classification

The framework begins by classifying the project into a structural system family and decomposing the construction programme into work packages. The activity breakdown should be detailed enough to identify temporary states and concurrent operations. A structural object may be a column, beam, slab, deck, brace, connection, formwork panel, shore, lifting insert or temporary platform. Temporary works must be represented explicitly rather than inferred from the permanent model, because the permanent model does not contain the information on which temporary-stage hazards depend.

Table 2: Structural-system families, construction activities and illustrative risk-generating conditions.

System family	Representative construction activities	Illustrative risk-generating conditions
Cast-in-place RC	Formwork/falsework; reinforcement; concrete pumping and placement; curing; striking/reshoring	Falsework instability; formwork blowout; falls from edges; rebar impalement/handling; hose movement; premature striking
Structural steel	Delivery and laydown; lifting; column/beam erection; temporary bracing; bolting/welding; decking	Suspended loads; dropped objects; incomplete-frame instability; falls; crane/rigging interface; hot work
Steel–concrete composite	Steel frame erection; metal deck placement; shear connectors; reinforcement; concrete placement; propping removal	Deck-edge falls; deck instability; connector/hot-work hazards; pour-stage overload; temporary prop failure; trade-interface conflicts

Table 2 is a preliminary classification for framework design, not an exhaustive hazard register. Project-specific method statements, applicable regulations, temporary-works calculations and competent-person reviews must be used to identify additional hazards.

4. THE PROPOSED FRAMEWORK

4.1 Overview

The framework has three layers, shown in Figure 1. The input layer comprises the structural, architectural and temporary-works models, the construction schedule and work breakdown, method statements and lifting plans, and regulatory and evidence sources such as incident and near-miss records and expert input. The core layer is a BIM-linked risk information model in which a structural-system classification and an activity decomposition support hazard scenario records, which are in turn assessed using likelihood, consequence and exposure ratings with recorded rationale, evidence and confidence. The output layer supports control selection, 4D visualisation

and a versioned audit trail. A feedback loop returns changes in design, sequence, temporary works, crew, equipment, weather or site conditions to the input layer and triggers reassessment.

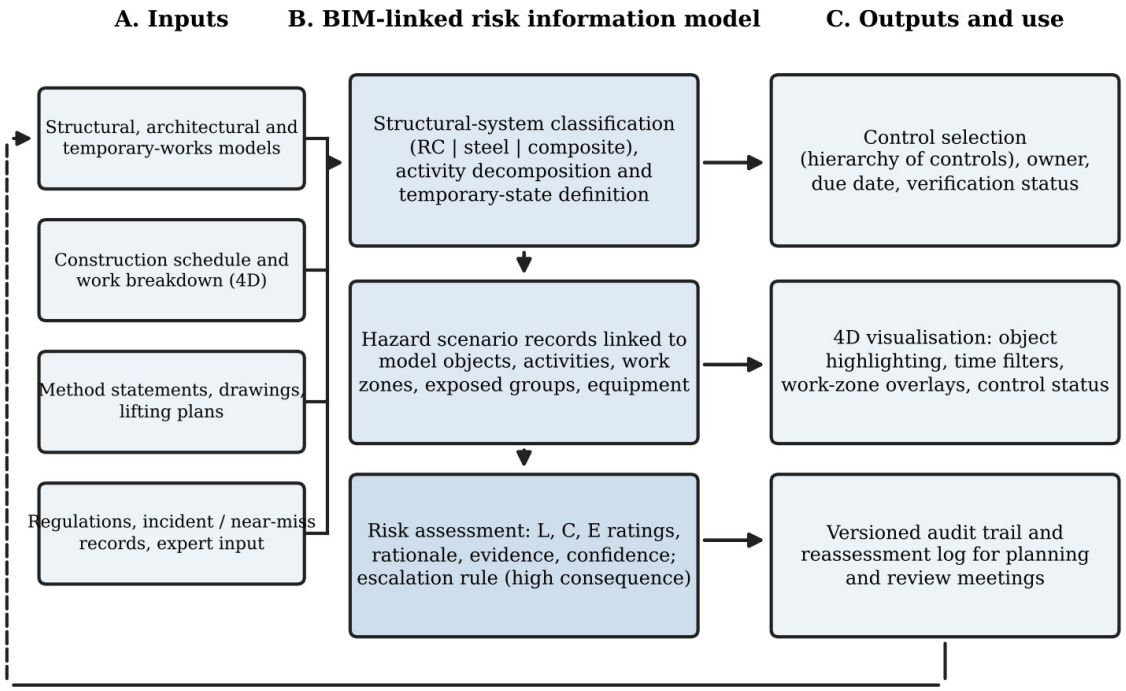


Figure 1: Overview of the BIM-enabled risk assessment framework.

4.2 BIM-linked risk information model

Each risk scenario is represented as a structured record linked to BIM objects and schedule activities. The minimum information entities are Project, StructuralSystem, ModelObject, TemporaryWork, ConstructionActivity, WorkZone, HazardScenario, ExposedGroup, Equipment, RiskAssessment, ControlMeasure, ResponsibleParty and EvidenceSource. Their relationships are summarised in Figure 2. Relationships are many-to-many where appropriate: one activity may affect several objects and expose several groups, while one hazard scenario may require several controls. The HazardScenario entity is the hub of the model because it is the entity at which structural object, temporary state, activity, location, exposed group and equipment are brought together; the RiskAssessment and ControlMeasure entities attach to it so that each assessment and each control is traceable to a specific scenario.

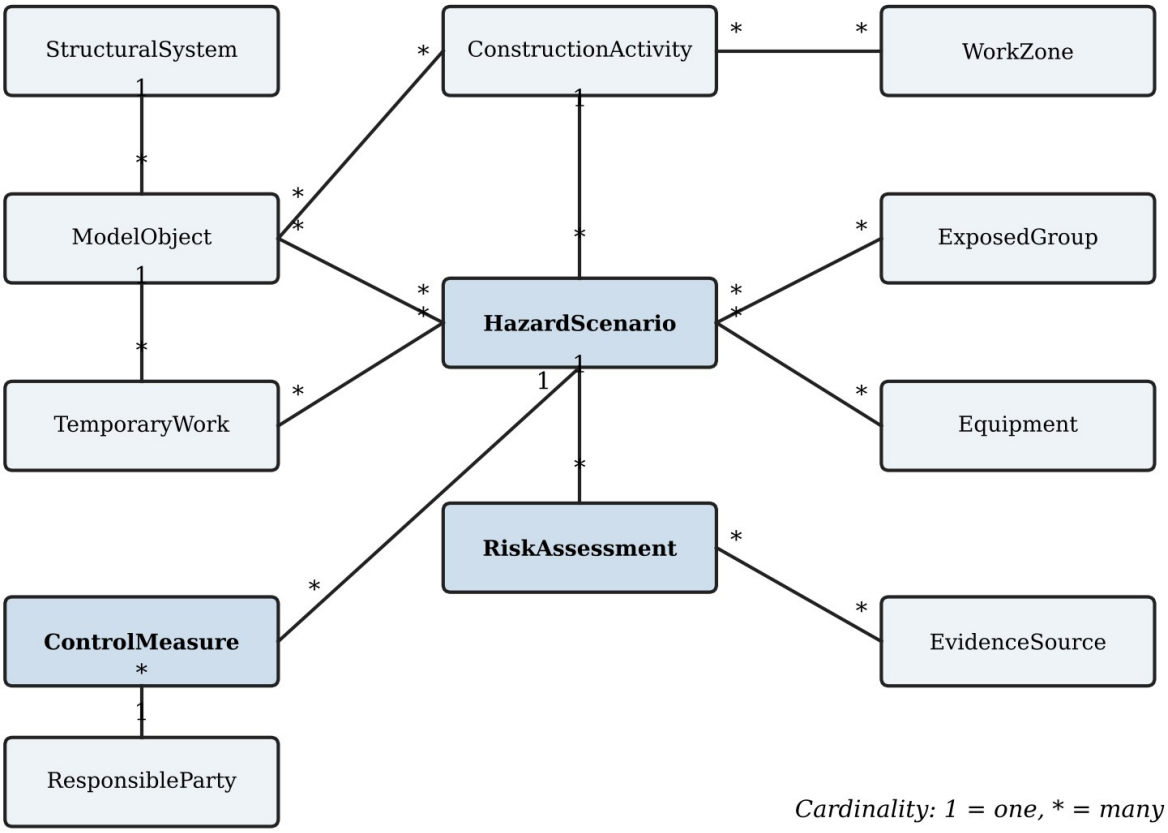


Figure 2: Entity–relationship view of the proposed risk information model.

Table 3: Proposed minimum information entities for the BIM-linked risk register.

Information entity	Minimum attributes	Purpose
ModelObject	GUID/ID; object type; level; location; system family	Identifies the permanent or temporary component involved
ConstructionActivity	Activity ID; start/end; predecessor; method; status	Provides the time and sequence context
HazardScenario	Hazard ID; event; cause; consequence; affected object/activity; temporary state	Describes the risk mechanism
Exposure	Group; location; duration/frequency; equipment interaction	Identifies who or what is exposed and when
RiskAssessment	Likelihood; consequence; exposure; score; confidence; assessor; date	Records the assessment and its provenance
ControlMeasure	Control type; description; owner; due date; verification	Connects assessment to an actionable response
EvidenceSource	Drawing; method statement; incident record; expert judgement; regulation	Supports auditability and later reassessment

Persistent object identifiers must be used so that links survive model exchange and federation. Where the native authoring platform does not support all risk attributes, a linked database or common data environment can store the risk records and reference the model object identifiers. Information exchange should be tested for identifier stability, property completeness and update behaviour, as specified in section 7.2.

4.3 Representing temporary states and time

A distinctive requirement of the framework is that intermediate structural states are first-class information. For each system, the sequence of construction activities is annotated with the temporary-state windows during which the structure depends on temporary supports, incomplete connections or staged load paths. Figure 3 shows these windows schematically for the three system families. In RC construction the critical windows are concrete placement and striking or reshoring; in steel construction they span lifting and the period before temporary bracing and connections give way to the permanent bracing system; in composite construction they include steel erection, deck installation, concrete placement and prop removal. The figure is a conceptual illustration of where explicit stability and exposure assessment is warranted. It is not drawn to scale and does not represent measured durations or relative risk.

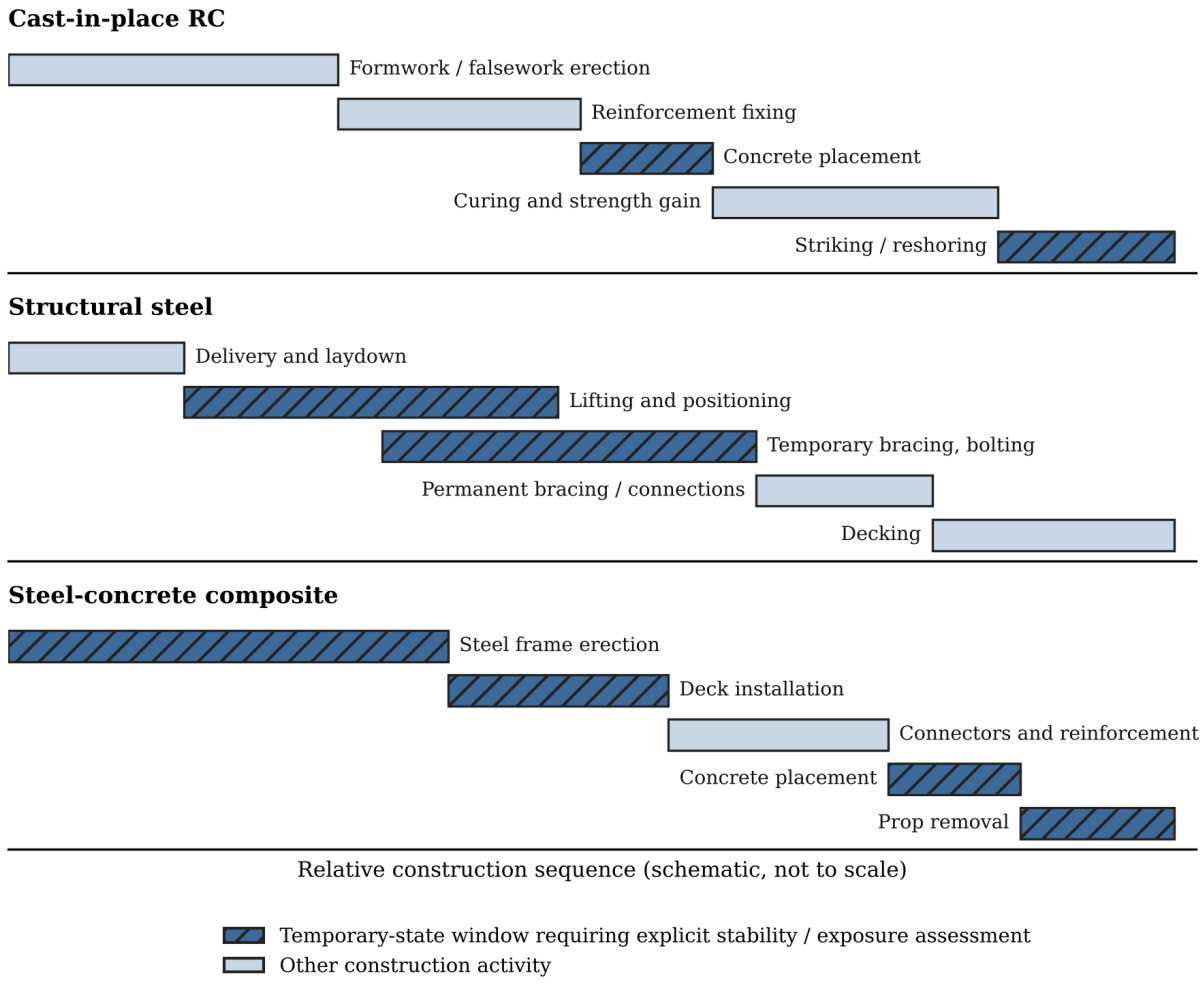


Figure 3: Schematic temporary-state windows in the three structural system families (conceptual; not to scale).

Each temporary-state window is bound to a defined set of model objects and a schedule interval, so that the risk record is valid only for that interval. If the sequence changes, the window moves, and the associated records are flagged for reassessment. This is the mechanism by which the framework addresses the temporal limitation of completed-structure models identified in section 2.

4.4 Risk estimation model

For an initial screening implementation, three ordinal dimensions are used: likelihood (L), consequence (C) and exposure (E), each rated on a five-point scale. The screening index is

$$R = L \times C \times E \quad (1)$$

where R is the screening risk index (range 1–125). This multiplicative index follows the likelihood–consequence–exposure logic used in BIM-integrated assessment (Lu et al., 2021). It is a prioritisation aid, not a calibrated probability of injury and not a substitute for a statutory risk assessment, and scores must not be interpreted as ratio-scale measurements. Table 4 gives the rating anchors, which require adaptation to the jurisdiction and project.

Table 4: Proposed ordinal rating anchors (to be adapted to jurisdiction and project).

Rating	Likelihood (L)	Consequence (C)	Exposure (E)
1	Rare under defined conditions	Negligible / first-aid level	Brief or isolated exposure
2	Unlikely	Minor injury or limited damage	Occasional exposure
3	Possible	Medical-treatment injury or moderate damage	Repeated exposure during an activity
4	Likely	Major injury, permanent harm or major damage	Frequent or prolonged exposure
5	Almost certain / expected without controls	Fatality, multiple serious injuries or catastrophic failure	Continuous or multiple-group exposure

Because a controlled scenario is assessed again after controls are verified, the residual index is calculated from the residual ratings:

$$R_{res} = L_{res} \times C \times E_{res} \quad (2)$$

Consequence is held at its baseline value in the residual calculation unless a control demonstrably changes the credible worst-case outcome (for example, by eliminating a suspended load over an occupied zone). This convention prevents controls that reduce likelihood or exposure from masking a severe credible outcome.

A preliminary decision band is used for workflow testing: 1–20 (routine monitoring), 21–50 (planned controls and supervisor review), 51–80 (priority controls and formal review) and 81–125 (work should not proceed until risk is reduced and authorised). The bands are provisional and must be calibrated with project stakeholders before operational use. In addition, an **escalation rule** applies: any scenario with $C = 5$ is escalated for formal review irrespective of R. Projects may tighten the rule, for example by also escalating $C = 4$ with $L \geq 3$. Figure 4 shows the index and bands for three exposure ratings.

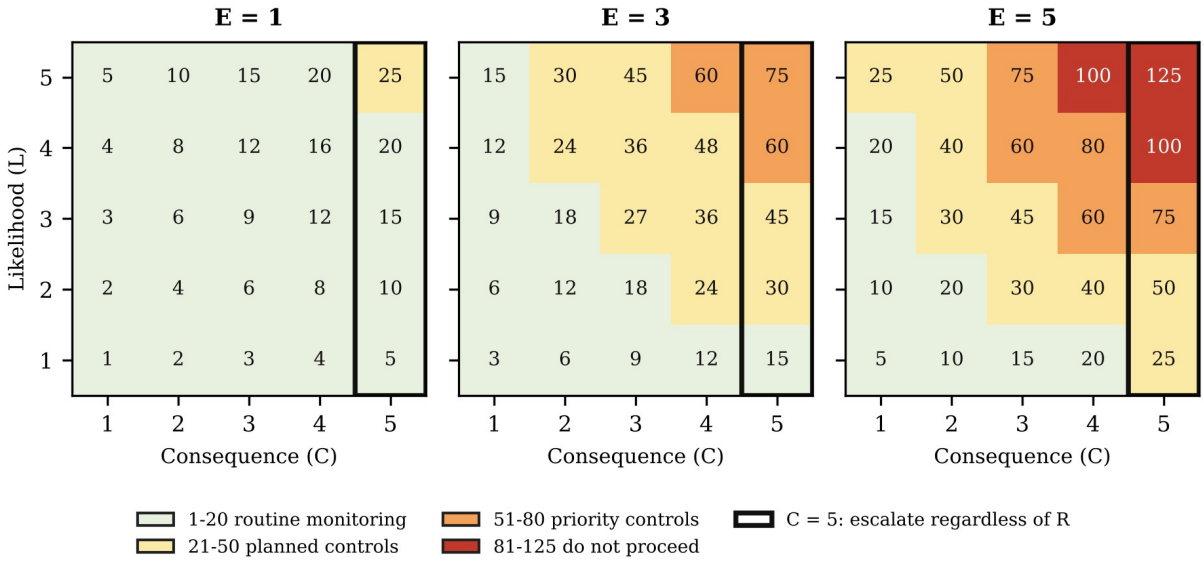


Figure 4: Screening index values and decision bands for exposure ratings E = 1, 3 and 5.

To avoid false precision, the risk record preserves the three component ratings, the rationale for each, the assessor, the date and a confidence level. Where reliable historical data are available, likelihood may be estimated using a defined exposure denominator and consistent incident definitions. Where such data are unavailable, expert elicitation must be labelled as judgement-based, and Bayesian updating may be considered as evidence accumulates (Khodabakhshian et al., 2025).

4.5 Analytical properties of the screening index

Because the screening index is the part of the framework most likely to be over-interpreted, its properties were examined analytically by enumerating all 125 combinations of L, C and E and applying the decision bands above. This is a property of the scoring scheme, not an empirical result, and it can be reproduced from the definitions given.

- **Limited resolution.** The 125 rating combinations yield only 30 distinct values of R. Up to nine combinations share a single value; for example, $R = 20$ arises from (L, C, E) = (2, 5, 2), in which a fatality is unlikely and exposure is occasional, and also from (2, 2, 5), in which only minor injury is credible but exposure is continuous. These are different risk situations with identical scores.
- **Skewed band occupancy.** The decision bands contain 71, 37, 13 and 4 of the 125 combinations respectively (56.8%, 29.6%, 10.4% and 3.2%). More than half of all rating combinations therefore fall in the lowest band.
- **High consequence can be hidden.** Of the 25 combinations with $C = 5$, 17 have $R \leq 50$ and 8 have $R \leq 20$. Eighteen combinations with $C \geq 4$ fall in the lowest band. Without the escalation rule, severe but unlikely or brief scenarios would be routed to routine monitoring.
- **Sensitivity to rating error.** Changing any single rating by one step changes the decision band in 162 of the 600 possible one-step changes (27.0%), and 80 of the 125 combinations (64.0%) have at least one neighbouring rating that lies in a different band. The proportion rises with band severity: 14.5%, 37.5%, 52.4% and 60.0% for the four bands in turn.

These results are consistent with the general concerns raised about ordinal risk matrices (Cox, 2008; Duijm, 2015). They justify three design decisions in the framework: the escalation rule for $C = 5$, the retention of the three component ratings alongside R, and the requirement to record rationale, evidence and confidence so that a rating near a band boundary can be reviewed rather than accepted as a single number. They also imply that the decision

bands should be treated as hypotheses to be calibrated through the validation programme in section 7, not as settled thresholds.

4.6 Assessment workflow

The workflow comprises eight steps and is iterative:

1. Prepare and federate the structural, architectural, temporary-works and site-logistics models; check model coordinates and object identifiers.
2. Link model objects to the work breakdown structure and construction schedule; verify that activity dates and dependencies represent the intended method.
3. Create activity-based hazard scenarios for each structural system, including temporary configurations and concurrent work.
4. Assign exposed groups, equipment, work zones and plausible consequences to each scenario.
5. Rate L, C and E; record evidence, assumptions, confidence and assessor identity; apply the escalation rule.
6. Select controls using the hierarchy of controls, prioritising elimination and substitution before engineering and administrative controls and personal protective equipment.
7. Visualise risk scenarios in 4D, using object highlighting, time filters, work-zone overlays and control-status indicators that link to the underlying rationale.
8. Reassess when the sequence, design, temporary works, workforce, equipment, weather or site conditions change; retain a dated audit trail.

A change to a beam erection sequence, concrete pour size, temporary support arrangement or access route may create new hazards or alter exposure. The model should therefore support versioning and reassessment rather than treat the risk register as a static deliverable.

5. FRAMEWORK APPLICATION: ILLUSTRATIVE SCENARIOS

This section illustrates how the framework structures risk scenarios. The scenarios are analytically derived from construction methods and the reviewed literature. They are not observations from a specific project and are not assigned empirical risk scores. The ratings used in the worked example in section 5.4 are hypothetical and are included only to demonstrate the calculation.

5.1 Cast-in-place reinforced concrete

For RC construction, the assessment should focus on the temporary load path and the condition of formwork and falsework before, during and after concrete placement. The BIM model should identify slab and beam formwork zones, shores, reshores, pour boundaries, access platforms, perimeter edges and concrete delivery routes. Schedule activities should distinguish formwork erection, inspection, reinforcement fixing, pre-pour approval, placement, curing, striking and reshoring. The risk record should capture the design basis and inspection status of temporary works, pour rate and sequence, placement equipment, access arrangements and the conditions required before supports are removed.

A representative scenario is local or progressive falsework failure during a concrete pour. In the causal structure described by Hadipriono and Wang (1986), the concreting operation is the trigger, while inadequate bracing, connections, foundations, design review or monitoring are enabling and procedural conditions. The framework mirrors this structure by recording the initiating condition and the latent conditions as separate attributes of the scenario. Consequences may include collapse, falls, struck-by events and damage to partially completed work. The scenario is linked to the affected formwork and falsework objects, the pour activity, the exposed workforce and the placing equipment, and to controls such as engineered temporary-works design, pre-pour inspection, load and sequence limits, exclusion zones and controlled striking approval.

5.2 Structural steel

For steel erection, the model should represent the temporary stability state of the frame at each erection stage. Columns, beams, bracing, connection locations, lifting points, crane positions, laydown areas, exclusion zones and access systems should be associated with erection activities. The register should distinguish the stability of an individual member during lifting from the stability of the partially completed frame after the crane releases it. Temporary bracing and connection completion status are particularly important attributes.

A representative scenario is instability of a partially erected frame before the permanent bracing system and required connections are complete. Potential initiating conditions include an erection sequence that creates an unstable configuration, inadequate temporary bracing, premature release of a suspended member, wind loading or incomplete bolting. The assessment links the hazard to the relevant frame bay and erection activity, identifies workers within the potential collapse zone, and specifies controls such as engineered erection sequencing, temporary bracing, connection verification, wind thresholds, lifting plans and exclusion zones.

5.3 Steel–concrete composite systems

Composite construction requires assessment of both steel erection and the subsequent activities that create composite action. The model should represent metal decking, edge protection, shear connectors, reinforcement, temporary props where required, concrete pour zones and the stage at which the slab reaches the specified strength. Scenarios may arise from deck installation at unprotected edges, local deck instability, hot work during connector installation, material stockpiling, or construction-stage loading before composite action is established.

A representative scenario is excessive construction-stage loading or instability during deck and concrete placement. The framework links deck panels, supporting beams, temporary props, pour sequence, placement equipment and storage zones. Controls may include verified deck span and load limits, an approved pour sequence, temporary propping design, restrictions on material stacking, edge protection and inspection before placement. The assessment must use the engineer-approved construction-stage design; the framework does not calculate or certify structural capacity.

5.4 Worked example of the screening calculation

Table 5 demonstrates the screening calculation, the decision bands and the escalation rule for the falsework scenario of section 5.1. **All ratings in Table 5 are hypothetical.** They were chosen to show how the index behaves and are not estimates of real risk, should not be generalised to any project, and must not be used to compare structural systems.

Table 5: Hypothetical worked example of the screening calculation for a falsework scenario.

Item	Baseline (before additional controls)	Residual (controls verified)
Scenario	Local falsework failure during slab pour; collapse with workers on and beneath the formwork	Same scenario with verified controls
Linked objects and activity	Slab formwork zone S2, shores, pour boundary; activity: concrete placement, level 3	Unchanged
Likelihood (L)	4 – Likely (no independent design check; field modifications possible)	2 – Unlikely (engineered design; pre-pour inspection signed off)
Consequence (C)	5 – Fatality or multiple serious injuries	5 – Unchanged (credible worst case remains)
Exposure (E)	3 – Repeated exposure during the pour	2 – Occasional (exclusion zone beneath formwork enforced)
Index R	4 × 5 × 3 = 60	2 × 5 × 2 = 20
Decision band	51–80: priority controls and formal review	1–20: routine monitoring
Escalation rule	Triggered (C = 5): formal review	Still triggered (C = 5): remains in formal review until all controls are verified
Evidence and confidence	Planning assumption; low confidence	Inspection records and design check; medium confidence (assessor-dependent)

The example shows why the escalation rule is necessary. After controls, R falls to 20, which falls in the lowest band, but the credible worst-case outcome has not changed. Without the rule, the scenario would be routed to routine monitoring as soon as the ratings were revised, even though the ratings themselves rest on medium-confidence evidence and a one-step change in either L or E would not alter the band. With the rule, formal review persists until the verification status of every control is closed. The example also illustrates that the baseline value of 60 can be produced by six different permutations of ratings 3, 4 and 5, and so the component ratings, not the score alone, must remain visible.

5.5 Cross-system comparison

Table 6: Qualitative comparison of construction-stage risk mechanisms and required BIM information.

Comparison dimension	RC system	Steel system	Composite system
Dominant temporary state	Formwork/falsework and reshoring configuration	Partially erected frame and temporary bracing	Steel frame plus deck, props and wet-concrete stage
Critical sequence dependency	Pour, curing, strength gain and striking	Lift, connect, brace and release crane	Erect steel, install deck/connectors, reinforce, pour and cure
Typical high-consequence scenarios	Falsework/formwork failure; falls; premature striking	Frame instability; suspended-load event; falls	Deck/edge failure; construction-stage overload; falls
Key BIM information	Pour zones, support layout, inspection and removal status	Member erection status, connection status, crane and bracing	Deck zones, prop layout, pour sequence and temporary loading
Important reassessment triggers	Pour method/rate change; support alteration; concrete strength status	Erection sequence change; wind; connection or bracing delay	Pour sequence or stockpile change; deck or prop alteration

The comparison does not establish a ranking of the three systems. A quantitative ranking would require comparable projects, consistent definitions of exposure and consequence, equivalent activity boundaries, and adjustment for confounding factors such as building height, geometry, project size, workforce experience, equipment and local regulatory requirements. What the comparison does show is that the *information* needed to assess risk differs in kind between systems: pour and support status for RC, erection and connection status for steel, and staged-load and prop status for composite construction. This supports the design choice of retaining system-specific scenario attributes inside a common assessment structure.

6. DISCUSSION

6.1 Answers to the research questions

RQ1. The analysis in sections 2.4 and 5 indicates that the three system families differ primarily in their dominant temporary states and critical sequence dependencies: falsework, pour and striking conditions for RC; the stability of the partially erected frame and crane release for steel; and the staged transition from steel-only to composite behaviour for composite construction (Table 6). **RQ2.** The information model in section 4.2 links objects, temporary works, activities, zones, exposed groups, equipment, hazards, assessments, controls and evidence around a central HazardScenario entity, with temporary-state windows bound to schedule intervals (Figure 2, Figure 3). **RQ3.** A common index with fixed rating anchors supports comparison of scenarios, while system-specific scenario attributes and the escalation rule prevent the index from erasing differences; the analytical examination in section 4.5 shows where the index is weak and how the framework compensates. **RQ4.** The validation protocol in section 7 specifies expert review, technical evaluation and comparative case studies, each with measures and hypotheses; none has yet been performed.

6.2 Positioning against existing work

The framework adopts established principles from the literature: linking hazards to model objects and schedule activities (Zhang & Hu, 2011; Jin et al., 2019), assessing likelihood, consequence and exposure (Lu et al., 2021), treating time and spatial exposure as essential (Tran et al., 2021; Kim et al., 2024), and recognising uncertainty

and the role of expert judgement (Khodabakhshian et al., 2025). Its distinctive contributions lie in the following. First, temporary works and intermediate structural states are treated as first-class information in the model, in line with what temporary-works failure studies indicate about the role of latent conditions (Hadipriono & Wang, 1986). Second, structural system is a classification dimension that organises scenarios without being used as a proxy for risk level. Third, the scoring scheme is accompanied by an explicit analysis of its limitations and by structural safeguards. This third point responds to the criticism that ordinal matrices are often adopted uncritically (Cox, 2008; Duijm, 2015). The paper does not claim that these features improve on existing tools; whether they do is an empirical question addressed by the protocol in section 7.

6.3 Critical appraisal of the scoring model

The multiplicative index is retained because it is familiar to practitioners, consistent with prior BIM-integrated assessment, and easy to implement, but the analysis in section 4.5 shows that it should be used with caution. Three issues deserve emphasis. First, resolution: with only 30 distinct values, ranking scenarios by R will produce frequent ties, and ties between structurally different scenarios convey no information about relative priority. Practitioners should therefore sort first by the escalation flag, then by C, then by R, and treat R as a tie-breaker within consequence level rather than as the primary ranking variable. Second, sensitivity: a single one-step rating difference moves the decision band in more than one quarter of cases, and the proportion is greater for the higher bands. Since inter-assessor differences of one step are plausible in judgement-based ratings, band assignment near a boundary should be reviewed by more than one assessor, and the confidence field should be used to flag such cases. Third, dependence: the index treats L, C and E as independent, whereas in construction they are often correlated. For example, extended exposure in a congested work zone may raise both E and L. Using the three ratings as a multiplicative product can therefore double-count or mask interactions. Alternatives, such as non-multiplicative rule tables, risk-priority schemes based on consequence and likelihood only with exposure as a modifier, or probabilistic models, may be preferable once suitable data exist, and the validation plan includes a comparison of the screening index against such alternatives where data allow.

6.4 Implementation and governance considerations

The framework positions BIM as an information integration environment rather than merely a three-dimensional visualisation tool. Its value depends on linking model objects to schedule activities, temporary works, risk scenarios, evidence and control status. A practical implementation should avoid duplicating information across disconnected spreadsheets and models. Risk attributes should be stored in a structured, version-controlled repository linked to stable model identifiers, in keeping with the principles of managing information on a common data environment. Model-based visualisation should lead users to the underlying assessment rationale rather than reduce risk to colour alone: a red/amber/green display without access to likelihood, consequence, exposure, assumptions and control status can create a false impression of certainty.

The framework can support early planning by making construction-stage hazards visible when alternative structural systems or erection sequences are considered. It should not be used to claim that RC, steel or composite construction is intrinsically safer. A defensible comparison requires equivalent functional scope and project conditions, and must separate inherent hazard mechanisms from the quality of the planned controls. Where BIM adoption is still developing, a phased implementation is realistic: begin with the risk register, scenario templates and schedule linkage for the temporary-state windows that matter most, and add 4D visualisation and automated checks as modelling maturity grows.

Data quality and governance remain decisive. Incomplete temporary-works models, inaccurate schedules, missing work-zone boundaries or outdated method statements can undermine any automated check. The framework therefore requires provenance and confidence fields and a defined process for approving changes. Expert judgement is essential where incident data are sparse, but its source and uncertainty must remain visible.

6.5 Limitations and threats to validity

The present manuscript proposes a conceptual framework and has not been empirically validated. It does not report interviews, questionnaire responses, accident statistics, model implementation results or a comparative case study.

The following threats to validity apply. *Construct validity:* the hazard taxonomy and rating anchors are derived from literature and analysis and may not match practitioners' categories. *Content validity:* the scenarios are illustrative and do not constitute a complete risk register. *Internal validity:* ordinal ratings are subject to assessor bias and anchoring, and the index cannot represent cascading failures or dependencies among ratings. *External validity:* the framework is developed for building superstructures and may not transfer to other project types, jurisdictions or levels of BIM maturity without adaptation. *Technology feasibility:* identifier persistence, model-schedule linkage and attribute storage depend on tool capabilities that have not been tested here. Finally, the framework is not a substitute for applicable occupational safety regulations, competent temporary-works design, structural engineering checks or project-specific safety management systems.

7. VALIDATION PROTOCOL AND FUTURE RESEARCH

To progress from a conceptual framework to an empirical contribution, a three-phase validation programme is proposed (Figure 5). The phases are sequential because each informs the next: expert review refines the taxonomy and rating anchors, technical evaluation tests the information model in tools, and case studies test the integrated workflow on project data.

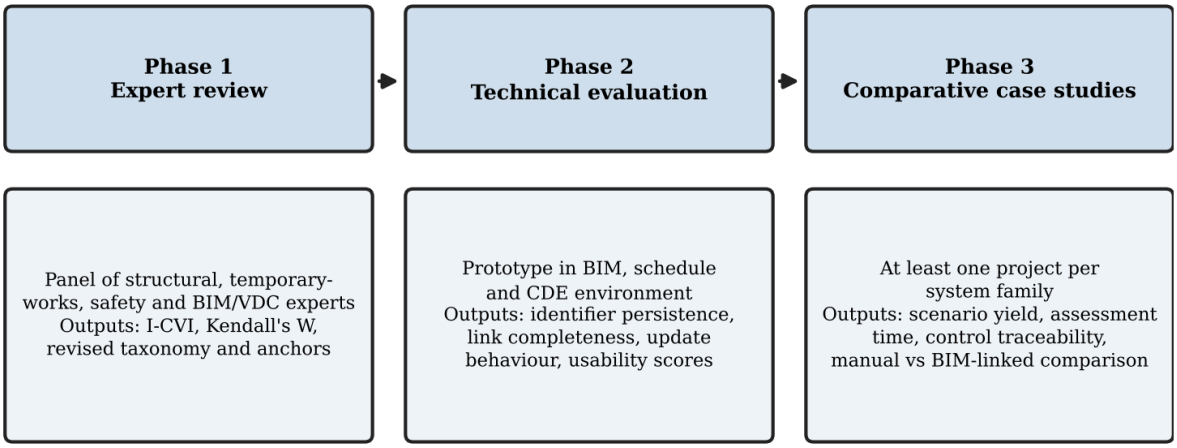


Figure 5: Proposed three-phase validation roadmap.

7.1 Phase 1: expert review

A purposive panel should include structural engineers, temporary-works designers, construction managers, safety professionals and BIM/VDC specialists with documented experience in at least one of the three structural system families. A panel of at least six experts, and preferably ten or more, is recommended so that content-validity indices are interpretable. Participants rate the relevance and clarity of each information entity, hazard scenario and rating anchor on a four-point scale. The item-level content validity index is

$$I\text{-}CVI = N_{agree} \; / \; N_{experts} \qquad (3)$$

where N_{agree} is the number of experts rating the item as relevant (3 or 4). For panels of six or more experts, values of about 0.78 or higher are commonly treated as acceptable (Lynn, 1986). Agreement among experts on ratings of the same standardised scenarios should be reported using Kendall's W for rankings and weighted kappa for pairs of assessors, interpreted against recognised benchmarks (Landis & Koch, 1977), together with intraclass correlation where ratings are treated as interval. The protocol should define recruitment, informed consent, participant

characteristics, missing-data treatment and institutional ethics approval. No expert ratings are reported in this manuscript.

7.2 Phase 2: technical and usability evaluation

Technical evaluation should test whether model identifiers persist through exchange, whether activity dates and dependencies are correctly linked, whether risk records update when model or schedule revisions occur, and whether visualised scenarios correspond to the correct objects and time windows. The traceability completeness of a project register can be measured as

$$TC = (N_{linked} / N_{total}) \times 100\% \quad (4)$$

where N_{linked} is the number of risk records linked to at least one valid model object and one schedule activity, and N_{total} is the number of records. Usability evaluation should examine whether intended users can find, interpret and act on risk information, using task-based tests and a standardised usability questionnaire.

7.3 Phase 3: comparative project case studies

The framework should be implemented on at least three projects or sufficiently detailed project models, ideally one for each structural system family. For each case, researchers should collect the structural model, construction schedule, temporary-works information, method statements, risk assessments and relevant incident and near-miss records where available. A consistent activity boundary and exposure definition should be applied. The comparison should report the number and type of scenarios identified, linkage completeness, assessment time, control traceability, and differences between the baseline manual assessment and the BIM-enabled workflow. Because a small number of cases limits statistical inference, results should be reported descriptively with effect sizes and uncertainty intervals, using paired non-parametric tests where appropriate, and the analysis plan should be registered before data collection.

7.4 Hypotheses and measures

Table 7 states the research propositions for empirical testing together with the measure and the outcome that would count against each.

Table 7: Research propositions, measures and disconfirming evidence for the validation programme.

Proposition	Measure	Evidence that would disconfirm
P1. Linking risk records to both BIM objects and schedule activities improves traceability compared with a document-only register.	TC (equation 4); proportion of controls traceable to an owner and verification status	No improvement in TC or control traceability over the baseline register
P2. Explicit modelling of temporary works and intermediate states identifies scenarios not readily visible in a completed-structure model.	Number and severity of additional scenarios identified by reviewers	Reviewers identify no additional scenarios or judge them non-credible
P3. 4D visualisation improves users' recognition of changes in exposure caused by sequence and workspace overlap.	Task accuracy and time in scenario-recognition tests with and without 4D views	No difference or poorer accuracy with 4D views
P4. The distribution of scenarios across RC, steel and composite systems varies with system-specific activities and project context; no universal ranking is expected.	Scenario profiles by system and project; sensitivity to project descriptors	A consistent ordering of systems that persists after adjustment for project descriptors
P5. Escalation and provenance fields reduce the misrouting of high-consequence scenarios to low bands.	Proportion of C = 5 scenarios in the lowest band with and without the escalation rule	No scenarios are affected by the rule in practice

8. CONCLUSIONS

This paper has proposed a BIM-enabled framework for assessing construction-phase risks across cast-in-place RC, structural steel and steel–concrete composite systems. The framework addresses an information gap: generic risk

registers can document hazards but may not preserve their relationship to structural objects, temporary states, work activities, time windows, exposed groups and controls. By linking these dimensions through a structured risk information model and a 4D workflow, the approach aims to make risk assessments more traceable, time-sensitive and comparable.

The principal contributions are a structural-system-oriented information model that treats temporary works and intermediate states as first-class information; a common screening index accompanied by an analysis of its properties, which shows that its 125 rating combinations collapse to 30 distinct scores and that a one-step rating change alters the decision band in 27% of cases; and the safeguards that follow from that analysis, namely an escalation rule for high-consequence scenarios, retention of component ratings, and recorded provenance and confidence. The illustrative scenarios show why sequence-dependent temporary states must be represented explicitly, and the cross-system comparison shows that the information required for assessment differs between systems even when a common scale is used.

The framework remains conceptual. Its reliability, usability and practical value must be tested through expert review, technical evaluation and comparative project case studies before claims of effectiveness can be made. Future work should implement the information model in a BIM and common data environment workflow, validate the hazard taxonomy against project evidence, calibrate the rating anchors and decision bands, compare the screening index with alternative prioritisation schemes, and evaluate whether 4D visualisation improves the quality and timeliness of construction risk decisions.

9. DECLARATIONS

Data availability. No datasets were generated or analysed in this study. The analytical results in section 4.5 can be reproduced by enumerating the 125 rating combinations under the definitions and decision bands given in section 4.4.

Conflict of interest. The author declares no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDIX A: PROPOSED RISK-RECORD DATA DICTIONARY

The following fields are proposed for a pilot implementation. Required fields should be agreed by the project team before data collection.

Table 8: Proposed data dictionary for a BIM-linked construction risk record.

Field	Data type / example	Requirement
Risk_ID	Unique text identifier, e.g. RC-POUR-001	Mandatory
System_Family	RC / Steel / Composite	Mandatory
Object_GUID	Persistent BIM object identifier	Mandatory where object-linked
Activity_ID	Schedule activity identifier	Mandatory
Temporary_State	Free text or controlled vocabulary	Mandatory where applicable
Hazard_Event	Concise event description	Mandatory
Cause_and_Condition	Initiating conditions and latent (enabling) conditions	Mandatory
Exposed_Group	Trade / role / public / equipment operator	Mandatory
Location_and_Time	Work zone, floor, activity start/end	Mandatory
L_C_E_Ratings	1–5 ordinal ratings and calculated index	Mandatory for screening
Escalation_Flag	Yes/No (C = 5 or project-tightened rule)	Mandatory
Evidence_and_Confidence	Source type, reference, confidence	Mandatory
Controls_and_Owner	Control measure, responsible party, due date	Mandatory
Review_Status	Open / controlled / verified / closed	Mandatory

APPENDIX B: ILLUSTRATIVE REGISTER ENTRIES

Table 9 gives example scenario entries for each system family to show the intended granularity of the register. Entries are illustrative, carry no ratings and are not a complete hazard list.

Table 9: Illustrative risk-register entries (no ratings assigned).

System	Scenario (initiating and latent conditions)	Linked objects and activity	Candidate controls
RC	Falsework instability during pour (excess pour rate; unapproved field modification; missing inspection)	Shores, formwork panels, pour zone; concrete placement	Engineered temporary-works design; pre-pour inspection; pour-rate limit; exclusion zone
RC	Premature striking of slab supports (strength not verified; programme pressure)	Reshores, slab; striking and reshoring	Strength verification before striking; controlled striking approval
Steel	Instability of partially erected frame (unstable sequence; inadequate temporary bracing; wind)	Frame bay, columns, beams, bracing; steel erection	Engineered erection sequence; temporary bracing; wind threshold; exclusion zone
Steel	Suspended-load event during lifting (rigging failure; premature release)	Lifted member, crane position, laydown; lifting	Lift plan; rigging inspection; connection verification before release
Composite	Deck instability or overload during pour (excess stacking; unverified deck span)	Deck panels, supporting beams, props; concrete placement	Verified deck load limits; approved pour sequence; propping design
Composite	Fall at deck edge during installation (incomplete edge protection)	Deck edge, perimeter; deck installation	Edge protection before deck access; access control; inspection